

NASA LANGLEY TRAJECTORY SIMULATION AND ANALYSIS CAPABILITIES FOR MARS RECONNAISSANCE ORBITER

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Mars Reconnaissance Orbiter will launch in August 2005 and will achieve Mars Orbit Insertion in March of 2006. It will then take approximately six months to use the process of aerobraking to shape its orbit into the desired science mapping orbit. This six-month period is arguably the phase of the Mars Reconnaissance Orbiter mission with the highest risk to the spacecraft, dipping to within 100 km of the planet. This process requires enough atmospheric drag to slow the spacecraft and circularize the orbit while remaining high enough in the Mars atmosphere as to not risk thermal degradation of spacecraft components. This paper will discuss the trajectory simulation and several analyses performed at NASA Langley Research Center to support a successful aerobraking phase of the Mars Reconnaissance Orbiter mission.

INTRODUCTION

Mars Reconnaissance Orbiter (MRO) will be launched in August 2005. The main science objectives of MRO are to conduct remote sensing science observations, identify and characterize sites for future landers, and provide critical telecom/navigation relay capability for follow-on missions. It will achieve a science mapping orbit of 225 km by 320 km¹. In its final science mapping orbit, MRO will take high-resolution images of the Martian surface using its visual and near-infrared capabilities. Before attaining its science mapping orbit, however, MRO must employ aerobraking for an estimated six months to reduce velocity and orbit size. This paper will focus on the aerobraking phase of the MRO mission. MRO is in a configuration during its aerobraking phase with the instruments pointing nadir and high gain antenna facing away from the velocity vector (aka, shuttlecock configuration). An image of MRO in its aerobraking configuration is shown in Figure 1.

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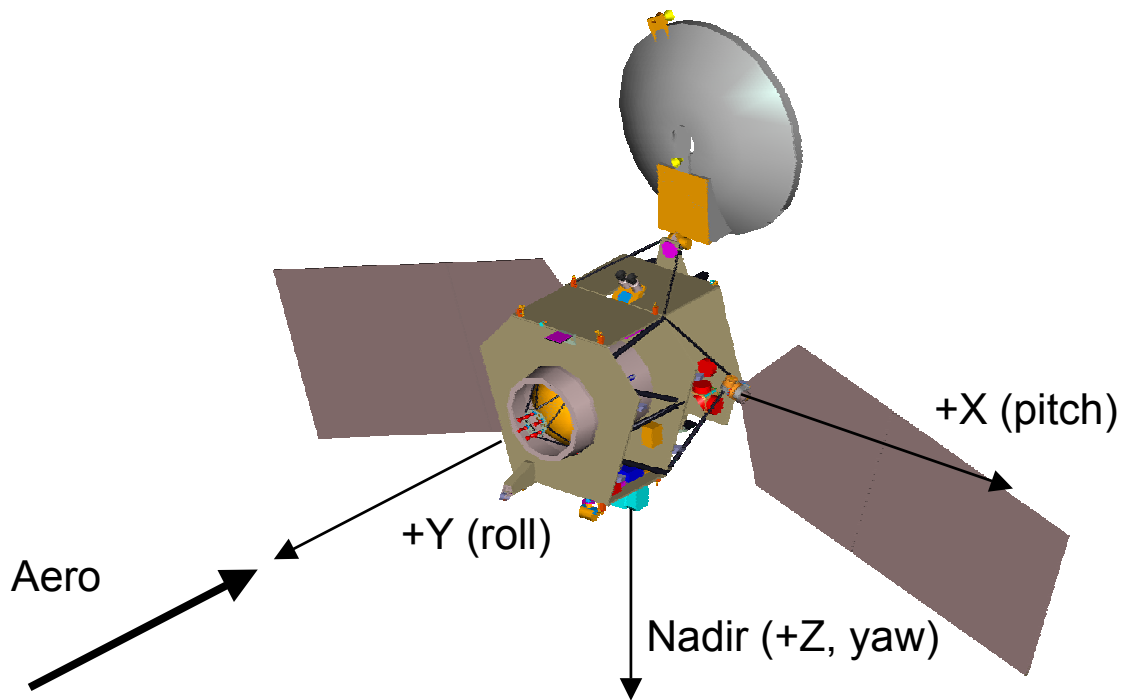


Figure 1. Mars Reconnaissance Orbiter in aerobraking configuration.

Several simulation tools across many organizations, namely the Jet Propulsion Laboratory's (JPL) Double Precision Trajectory program (DPTRAJ) and Program to Optimize Simulated Trajectories (POST) at Lockheed Martin Astronautics are utilized for the aerobraking phase that predict mission performance statistics and aerobraking progress. This paper will address simulation techniques and capabilities at NASA Langley Research Center with the simulation tool, Program to Optimize Simulated Trajectories II (POST2). POST2 (a significant upgrade of the previous environment POST) has vast heritage as a reputable Mars spacecraft simulation tool². Most recently, it has been used during the aerobraking operations phase for 2001 Mars Odyssey³, as the prime simulation for the Entry, Descent, and Landing (EDL) phase of the Mars Exploration Rovers (MER) Spirit and Opportunity⁴, and POST2 is used in the design phase of the 2007 Phoenix lander⁵ and 2009 Mars Science Laboratory (MSL)⁶.

POST2 MODELS

Several models are incorporated into the POST2 environment for simulation use with MRO. These engineering level models are considered the best software representation of the system or physical process. These models undergo detailed testing and checkout to ensure their correct implementation into the POST2-based MRO simulation. The current models in POST2 as of this publication are indicated below, however these models are changed as updates are available or the MRO project chooses to use another one.

The MRO project specified planet model includes atmosphere and gravity models as well as an approved set of planetary constants. The atmosphere model used for the POST2 trajectory simulations is Mars-GRAM 2001. Mars-GRAM is an engineering model of the Martian atmosphere that incorporates several global circulation models and previous mission data⁷. The density, temperature, pressure, and winds generated by Mars-GRAM are a function of altitude, date, latitude, and longitude of the spacecraft. As prescribed by the MRO Planetary Constants and Models document⁸, the trajectory analysis incorporates the MGS85F2-IAU2K-33962 gravitational model, which is an 85 degree and order gravity model. This model is often truncated to degree and order of 20 to reduce computational simulation time. The oblate spheroid Mars planet model consistent with this gravity model is shown in Table 1.

Table 1. Mars Planet Shape Parameters

Reference Radius (r_{REF})	3396.2 km
Mars Gravitational Parameter (μ)	42828.376212 km ³ /s ²
Equatorial Radius (r_E)	3396.19 km
Polar Radius (r_P)	3376.20 km
Mars Flattening Factor (f)	-0.00588600756

An aerodynamic database was developed at NASA Langley that provides force and moment coefficients for an expected range of atmospheric densities and spacecraft attitudes⁹. As indicated in the reference, this database was created by applying free molecular and Direct Simulation Monte Carlo (DSMC) computational fluid dynamics to a spacecraft geometry model with an area of 37.5 m² and a reference length of 13.6 m.

The last model discussed here is the aerobraking maneuver (ABM) logic implemented into POST2. As the trajectory progresses, ABMs will be necessary to maintain the defined heat rate or dynamic pressure corridor. At a particular apoapsis, the simulation will pause to spawn a second simulation as a predictive technique. This second simulation will propagate ahead for a given number of orbits or days as input by the user. At the end of this secondary propagation, the maximum heat rates at each drag pass in the secondary simulation were compared to the upper and lower corridor lines. If a boundary is exceeded, a maneuver will be performed in the primary simulation at the apoapsis where the simulation was paused. The size and magnitude of the maneuver is determined by the relative position of the violating heat rate to the corridor limit. It is targeted to a user input position within the corridor.

AEROBRAKING BASELINE TRAJECTORY

A typical aerobraking trajectory begins at the first apoapsis following Mars Orbit Insertion (MOI). The apoapsis state and a table of walk-in ABMs are provided by JPL. These initial walk-in maneuvers place the spacecraft within the bounds of the corridor described later. The trajectory is then propagated until the final apoapsis altitude reaches

450 km. After this point, an aerobraking termination maneuver will be made to complete the aerobraking phase. This maneuver is not included in the current simulation (which ends at walk-out), but can easily be added if the MRO project deems it necessary.

The MRO baseline aerobraking trajectory targets aerobraking completion to a specified local mean solar time (LMST). The MRO Navigation Team is responsible for defining the baseline aerobraking trajectory that will be used during aerobraking operations. The POST2-based simulation is also capable of developing a baseline, but NASA Langley's responsibility for this mission is an independent assessment and analysis of the project defined baseline. Thus, a baseline aerobraking trajectory is determined using POST2 so that it can be compared with the project generated baseline.

After MOI in March of 2006, the spacecraft orbital period is approximately 35 hours. The first phase of aerobraking targets aggressively to 3:15 pm LMST and then retargets to 3:00 pm LMST after the spacecraft has achieved a 5 hour orbital period (approximately 145 days and 250 orbits into the MRO aerobraking phase). This method helps to increase safety margins by aerobraking more aggressively early in the aerobraking to increase margin. During aerobraking, a corridor is designed to keep the spacecraft within specified limits to maintain effectiveness of aerobraking while preserving thermal safety. Note, this corridor may be defined either as a dynamic pressure corridor as was done during the Mars Global Surveyor mission¹⁰ or as a heat rate corridor, as done during the Odyssey mission³. ABMs are performed at apoapsis to maintain the spacecraft within this defined corridor. One ABM is allowed within a 24-hour period to ease the operational burden of uploading ABM sequences and to reduce the total number of ABMs. Another constraint on the system is that MRO must maintain a 48-hour lifetime above 300 km in apoapsis altitude. This constraint translates into a lower dynamic pressure limit toward the end of aerobraking. A typical aerobraking mission trajectory runout of dynamic pressure is shown in Figure 2. Maneuver size is expressed on the right-hand side of Figure 2. Maneuver size does not exceed 1 m/s in this analysis except for the initial walk-in phase of aerobraking.

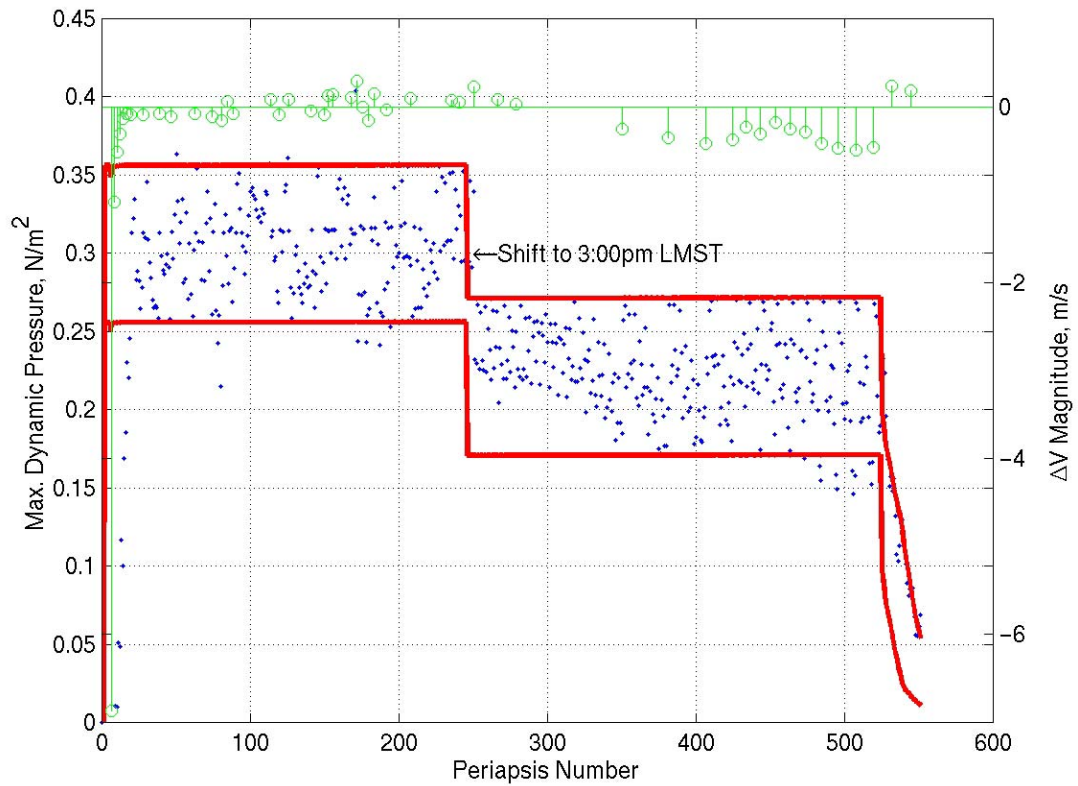


Figure 2. MRO aerobraking trajectory dynamic pressure corridor and maneuver magnitudes.

The aerobraking baseline reference trajectory is also shown relative to a heat rate corridor. This representation is shown in Figure 3. The ERD line to which margin is calculated is also identified. This line indicates the maximum heat rate at which the spacecraft components have been tested and validated.

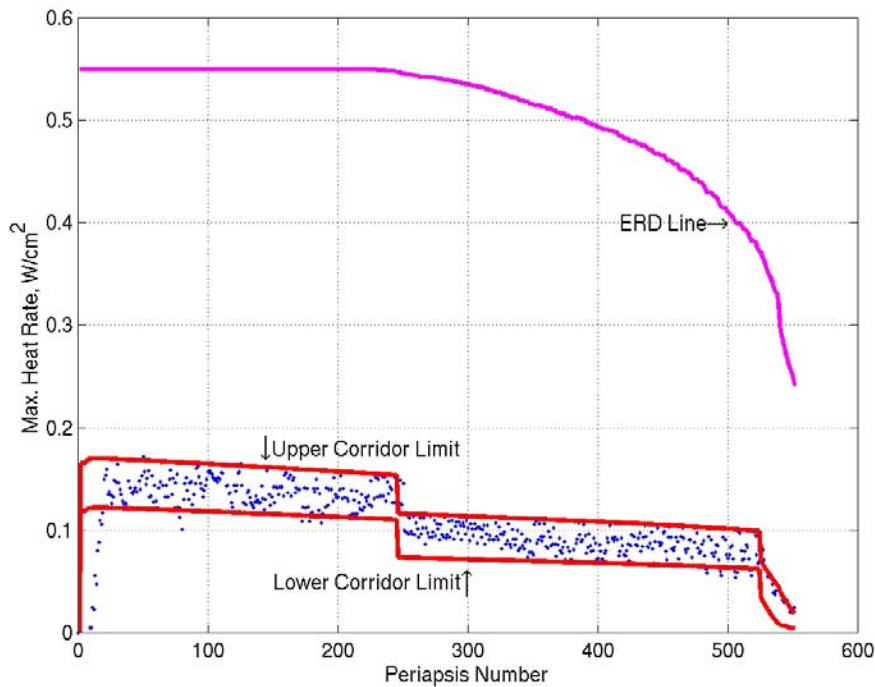


Figure 3. MRO aerobraking trajectory heat rate limits.

Reference trajectory statistics are shown in Table 2. These statistics are valuable in comparing simulations at other organizations and in generating information required by the primary science navigation team in organizing the science mapping orbit information.

Table 2. Statistics for baseline reference aerobraking trajectory

Duration of Aerobraking	184 days
Total Number of Orbits	551
Total ΔV	16.8 m/s
Total Number of ABMs	49
Final Periapsis Latitude	20.5°
Final Inclination	92.87°
Final Eccentricity	0.05

REFERENCE GLIDESLOPE

POST2 has been also been used to devise a potential reference “glideslope” or status indicator for aerobraking progress during operations. This reference, although unrealistic in flight due to the amount of propellant used, forces the simulated spacecraft into a trajectory that remains in the direct center of the dynamic pressure or maximum heat rate

corridor to achieve the desired LMST. This approach is used to provide an “average” or ideal aerobraking trajectory, see Figure 4. During operations, this glideslope, often seen in the form of period versus time (as shown in Figure 5), would indicate how close to the LMST glideslope line that MRO would be at a given instant during aerobraking operations. Figure 5 illustrates the glideslope for the POST2 generated reference baseline trajectory. This philosophy worked well during Mars Odyssey operations and indicated when the operations team should consider being more or less aggressive at certain parts of the aerobraking phase³. Straying too far from the glideslope during operations could require a change in aerobraking strategy during the aerobraking phase.

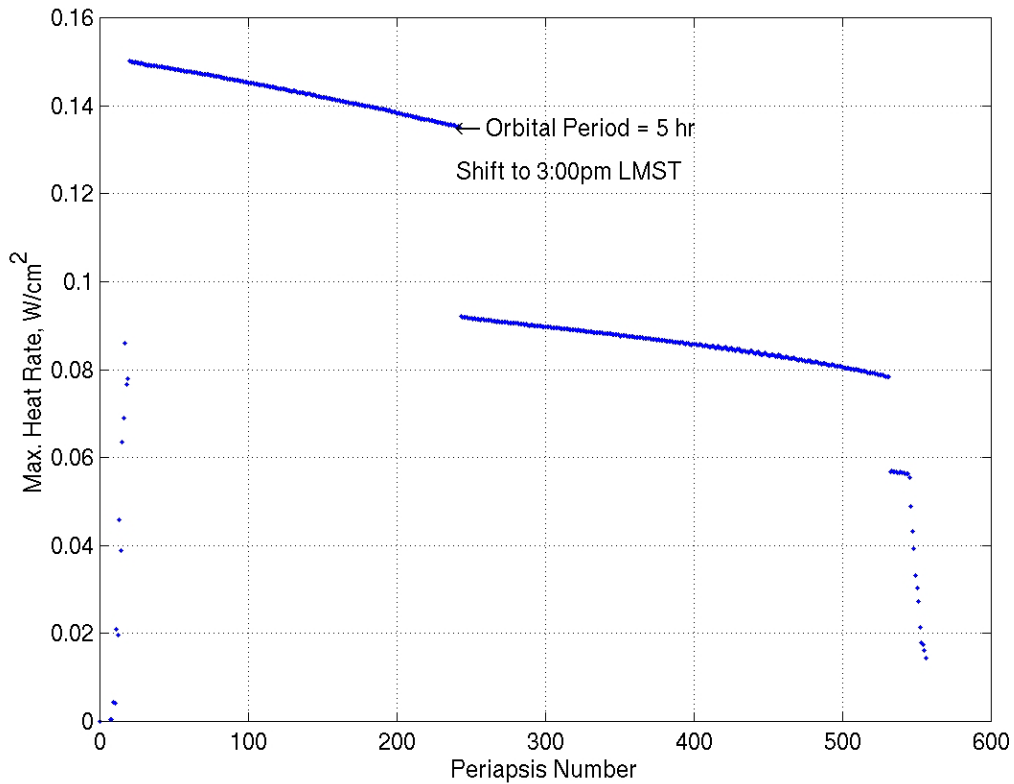


Figure 4. Heat rate profile for reference glideslope simulation.

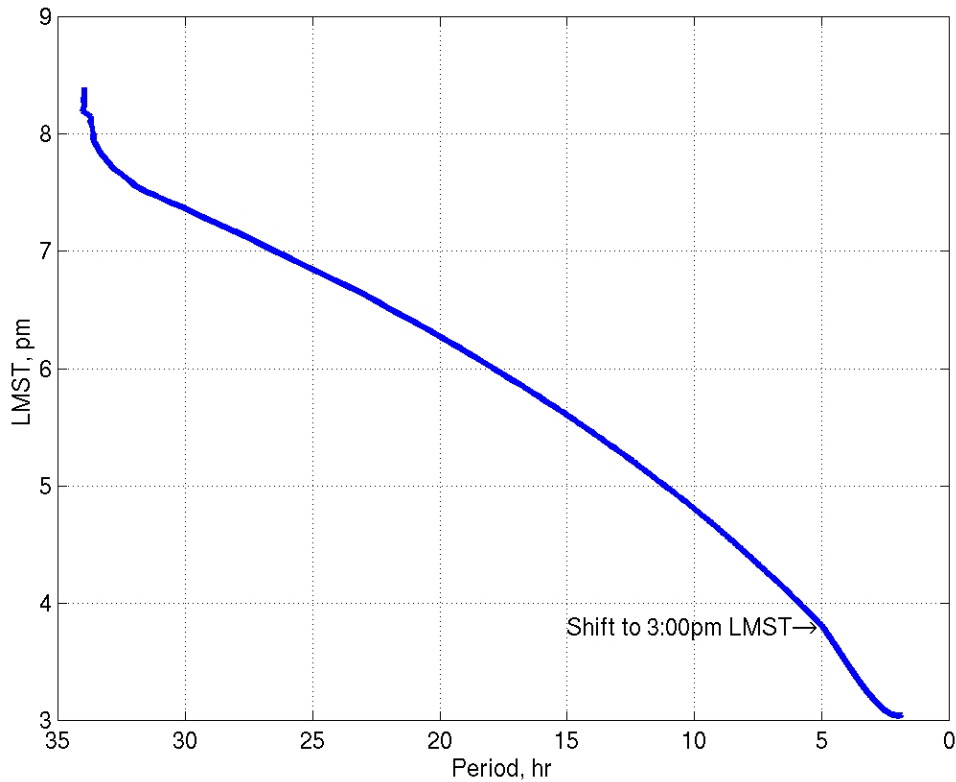


Figure 5. Potential aerobraking reference glideslope.

POP_UP ANALYSIS

Other trade studies have been assessed using POST2 to examine the effects of unplanned events during aerobraking that could result in larger maneuvers, termed “pop-up” maneuvers, to temporarily exit the atmosphere and suspend aerobraking operations. POST2 has been used to identify, at certain phases of aerobraking, how long the spacecraft may remain exoatmospheric before lowering back to aerobraking altitudes while maintaining a healthy margin and still achieving the required final LMST.

The study shown in Figure 6 is an analysis of a pop-up maneuver made during either the beginning of aerobraking (orbit 50), middle of aerobraking (orbit 100 or orbit 200), or the end of aerobraking (orbit 300). This analysis was performed to identify the length of time that MRO could remain exoatmospheric before an additional walk-in to the atmosphere would allow the aerobraking phase to reach completion at the required 3:00pm LMST. The constraint on the post-pop-up trajectory is that MRO must maintain a minimum of 100% aerobraking margin relative to the ERD line.

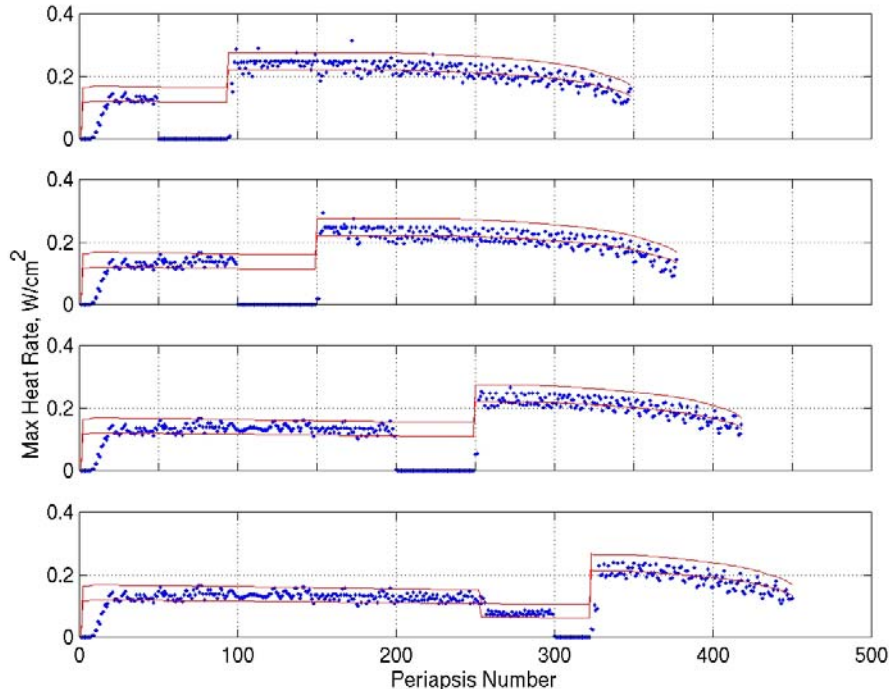


Figure 6. Effect of pop-up maneuver on maximum heat rate.

As shown in Figure 6, the length of time allowed before a necessary walk in decreases as the pop-up maneuver occurs later in the aerobraking phase. The main reason for this drastic decrease in time is that the orbital period decreases rapidly over time. A table of pop-up time and orbit duration is shown in Table 3. For example, if the maneuver occurs on orbit 50, 44 orbits and a corresponding 41 days are allowed before aerobraking must continue again to reach 3:00pm LMST. No analysis was performed after orbit 300 because any maneuver made later than orbit 350 would require a smaller margin to the ERD line or a later LMST constraint. Note that there is no obvious distinguishable trend to the orbits or number of exoatmospheric days allowed. There are several reasons for this trend. Firstly, the ERD line is not constant – it is indicative of a lower heat rate towards the end of aerobraking, affecting the 100% margin line. Secondly, there is a shift in the reference aerobraking trajectory to target from 3:15 pm LMST to 3:00 LMST. The pop-up analysis changes depending on where this shift occurs. For this analysis and for the reference trajectory, this shift occurs when the orbital period reaches 5 hours. Lastly, for this analysis, the lifetime constraint was not taken into account. If a pop-up maneuver were to occur, the 100% margin would not be maintained through the remainder of the aerobraking phase since there would also be a lifetime constraint taking effect towards the end of aerobraking that would significantly decrease the allowable heat rate limit.

Table 3. Pop-up maneuver analysis results.

Orbit Number of Popup Maneuver	Duration of Popup (days)	Number of Exoatmospheric Orbits	Duration of Aerobraking (days)
50	41	44	171
100	28	50	173
200	14	50	175
300	5	23	177

It is also shown in Figure 6 that the total duration of aerobraking is smaller when the pop-up maneuver is made toward the beginning of aerobraking. The reason for this small duration is that the aerobraking margin after the pop-up maneuver is held to 100%, smaller than the normal margin held during this phase. Typically, MRO maintains a 200-300% margin throughout the aerobraking phase. A more aggressive approach is taken after the pop-up maneuver is made to make up for the exoatmospheric orbits, but such an aggressive stance is unnecessary as the duration is shortened to 171 days. Figure 7 shows the effect of when popup occurs on LMST.

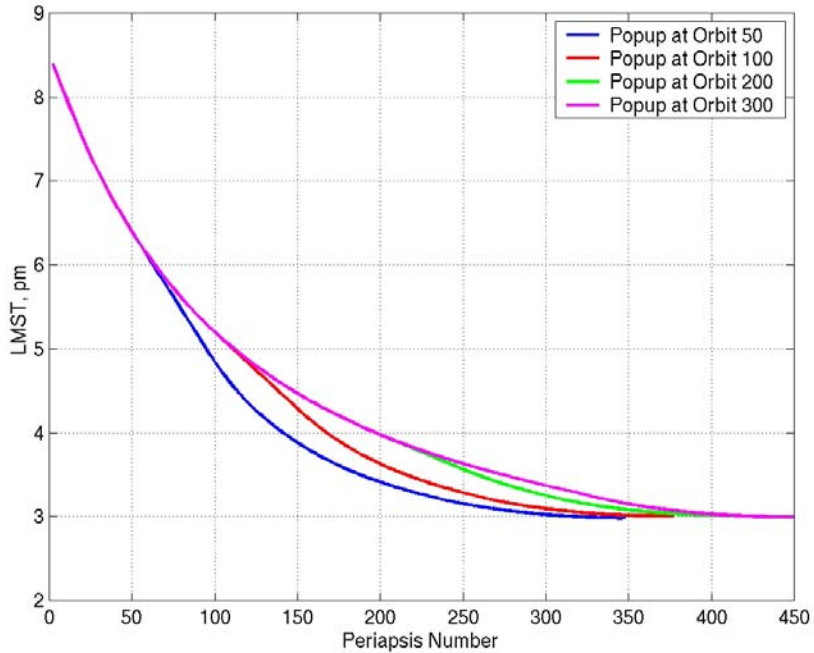


Figure 7. Effect of pop-up maneuver on local mean solar time.

Monte Carlo Analysis

Aside from nominal trajectory runouts, other trade studies and sensitivity studies are being performed to ensure a successful mission for MRO. At NASA Langley Research

Center, Monte Carlo analysis is used to obtain statistical analysis of events in question. Nominal values were used for single case trajectories and these values were dispersed to simulate off-nominal cases that may arise due to uncertainties in given parameters. Dispersed inputs were generated by a random number seed, maintaining the values of individual parameters between given $\pm 3\sigma$ values. Mars-GRAM dispersions are handled internally given an initial random seed⁷. The results of these Monte Carlo analyses determine several parametrics at certain phases of aerobraking that indicate aerobraking performance, or the probability that a given trajectory will be achieved within a specified time.

Some Monte Carlo pre-aerobraking studies involve the spacecraft state change when MRO approaches a resonant orbit. Figure 8 illustrates the large inclination change that can occur as the spacecraft reaches a resonant 12-hour orbital period. Perturbations in this simulation of 500 trajectories include a $\pm 6\%$ 3σ variation in aerodynamic Axial force coefficient (C_A), a $\pm 10\%$ 3σ variation in aerodynamic Normal force coefficient (C_N) and $\pm 60\%$ 3σ variation in atmospheric density. These values are typical of a daily Monte Carlo analysis performed at NASA Langley during 2001 Mars Odyssey aerobraking operations and will continue to be used for MRO aerobraking operations. Other parameters that may be used in Monte Carlo analysis are variations in atmospheric dust opacity parameter (τ) and/or vehicle center of gravity locations. For MRO operations, additional parameters can be dispersed in the Monte Carlo analyses as the project indicates a desire for their inclusion.

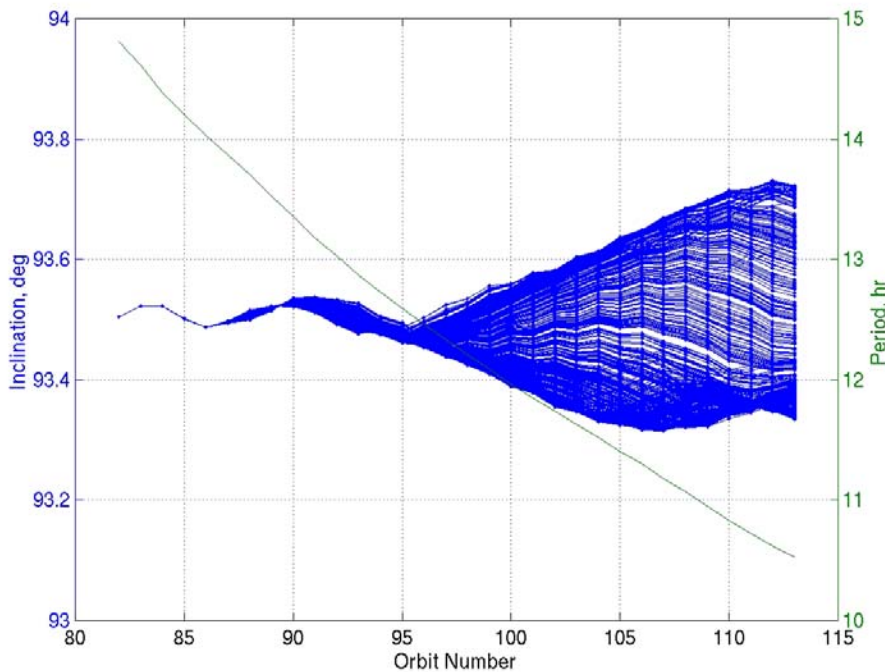


Figure 8. Monte Carlo results on orbital inclination at a 12-hour resonant orbital period.

Figure 8 indicates that during aerobraking operations, care must be taken in studying the Monte Carlo results when approaching resonant orbits (e.g., 6, 8, 12, 24 hour orbital periods). A single simulation could vary significantly when maneuver decisions must be made. Slight differences in the trajectory prior to a resonant orbit can lead to significant differences as aerobraking progresses.

Maneuver decisions can be made with the help of Monte Carlo analysis. During aerobraking operations of MRO, maneuvers will be made at several apoapses to keep the spacecraft within the corridor. Monte Carlo studies will be performed to assess statistics such as the time before the next required maneuver given specific choices of maneuver magnitudes, or the maneuver magnitude that is necessary to remain in the corridor for the longest period of time without an additional maneuver.

Figure 9 illustrates a typical daily Monte Carlo that will be performed at NASA Langley during MRO operations. In this example starting at periapsis 183, no maneuvers are to be performed; the Monte Carlo analysis is merely used to predict where the spacecraft will lie within the heat rate corridor in the subsequent 20 orbits.

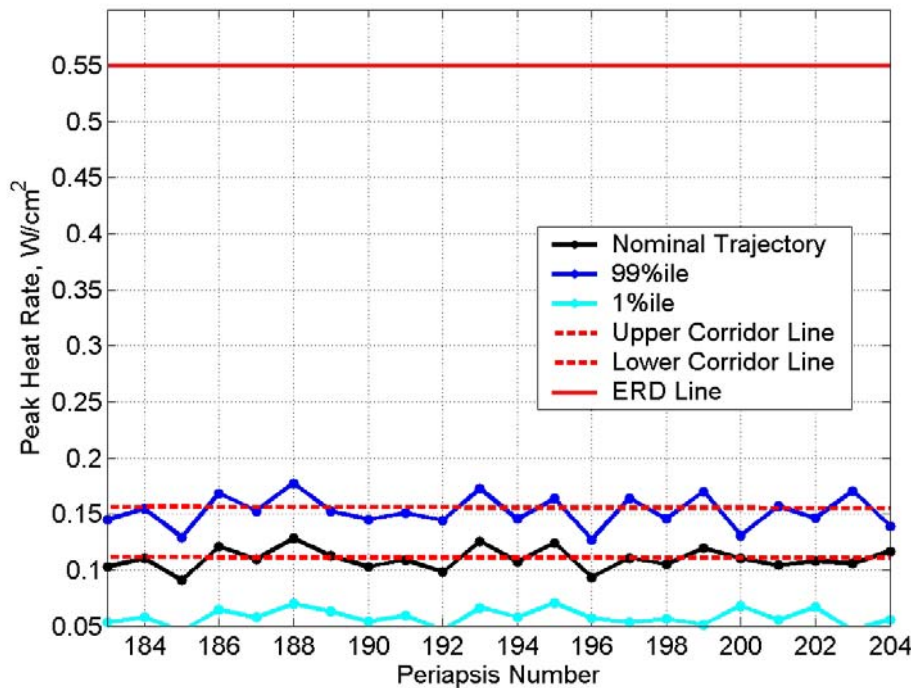


Figure 9. Monte Carlo results for typical aerobraking ABM slot.

It is shown in Figure 9 that the nominal trajectory hovers around the lower corridor line and that the 99 %-ile of the Monte Carlo results bounce about the upper corridor line. Neither line is in danger of breaching either the 200% or the 100% margin line. Since the

nominal trajectory is at a relatively low level, a maneuver may be considered to aerobrake more effectively (i.e., more in the center of the corridor).

ABM DECISIONS

During MRO aerobraking operations, ABMs will be necessary to maintain the spacecraft within its thermal corridor limits. POST2 may be used to help in the decision-making process as to the size and direction of a maneuver on any given orbit. For this process, NASA Langley develops an “ABM sweep” of a range of maneuver possibilities for a given apoapsis. The first option to always consider is to make no maneuver for the given maneuver slot. This option is compared to maneuvers that may be chosen from the onboard velocity increment (DV) menu, a pre-determine list of options of DV previously uploaded to the spacecraft. Figure 10 illustrates one scenario for an ABM sweep at apoapsis 184.

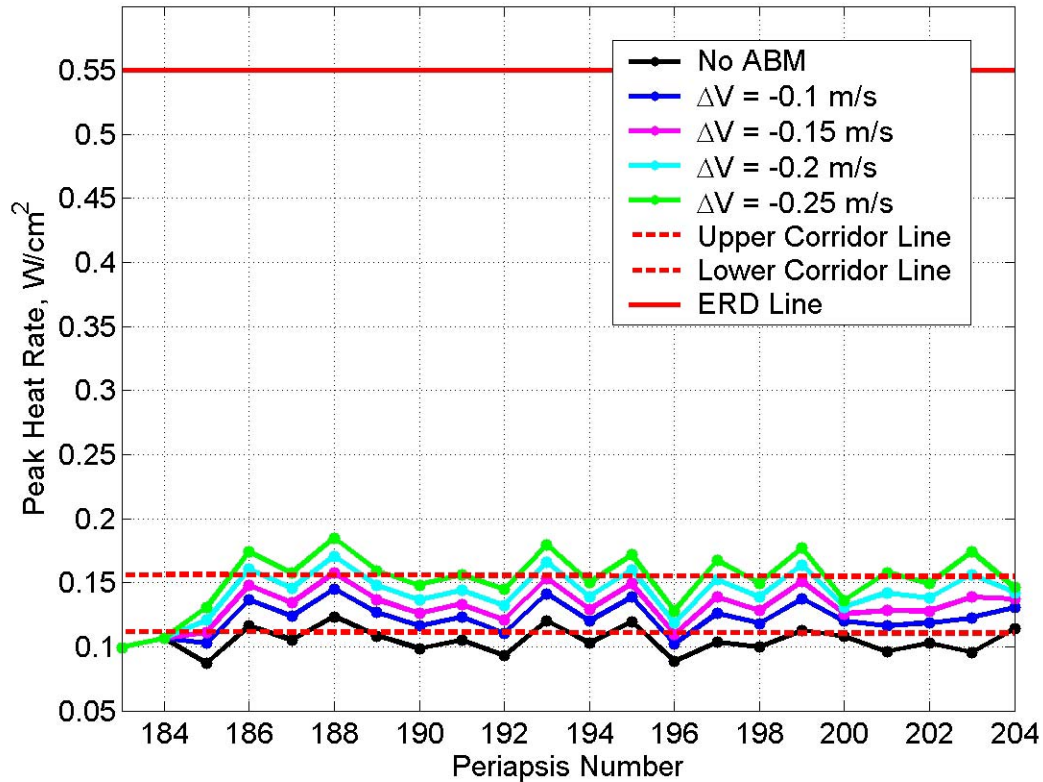


Figure 10. ABM sweep at orbit 184.

It may be decided that the appropriate maneuver for Apoapsis 184 is -0.15m/s . Once this maneuver is determined, another Monte Carlo analysis is run using the suggested maneuver and statistics from that Monte Carlo are used in final maneuver decision.

Figure 11 shows the Monte Carlo results using the suggested -0.15m/s ABM at Apoapsis 184.

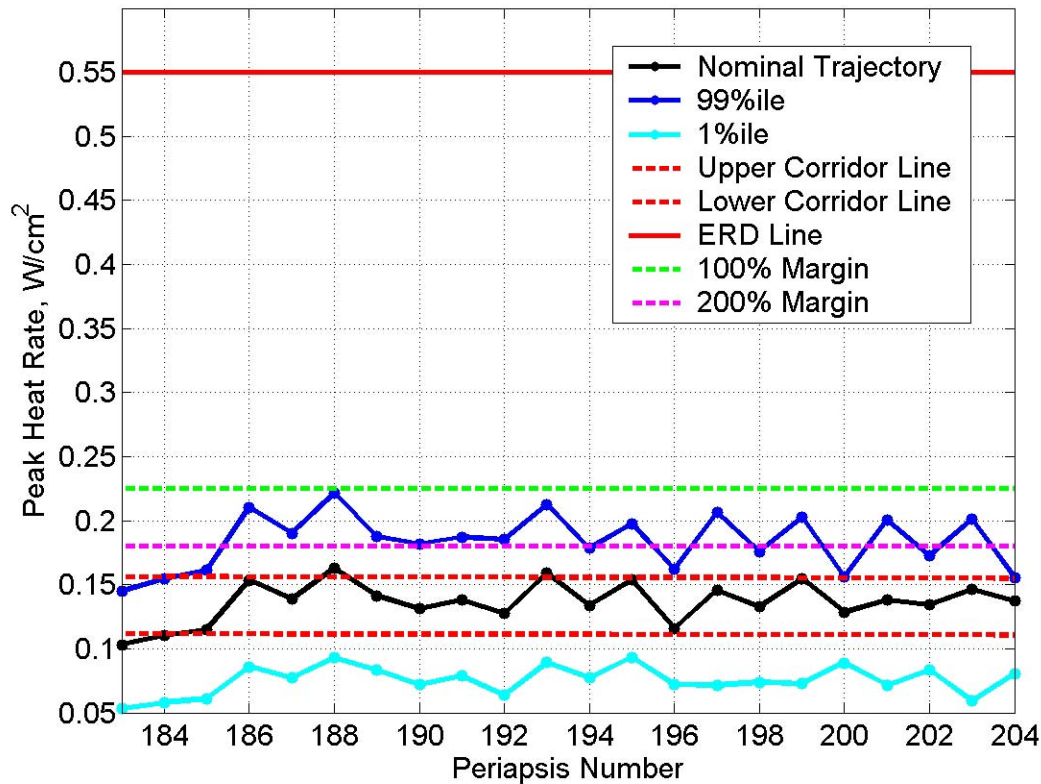


Figure 11. Monte Carlo analysis of maneuver at apoapsis 184.

As shown in Figure 11, the nominal trajectory is now comfortably within both corridor lines. The 99%-ile Monte Carlo results are still below the upper margin line (100% in this example), therefore the size of this maneuver would be appropriate to continue with for aerobraking operations.

These and other analyses are being performed at NASA Langley Research Center to help develop the aerobraking strategy that will be used during MRO aerobraking operations. During aerobraking operations for MRO, the Flight Mechanics team at NASA Langley will provide to the MRO Navigation team: support for maneuver decisions; an overall status of the effect of aerobraking on the MRO orbit; and a forecast of aerobraking results for the upcoming time period. This work will be done on a weekly or a more frequent basis to ensure success in MRO aerobraking operations.

NOMENCLATURE

ρ	atmospheric density, kg/km ³
τ	atmospheric dust opacity parameter
Q	dynamic pressure, N/m ²
ABM	aerobraking maneuver
DPTRAJ	Double Precision Trajectory program
DSMC	Direct Simulation Monte Carlo
DV	Velocity Increment, m/s
EDL	entry, descent, and landing
ERD	Environment Reference Document
JPL	Jet Propulsion Laboratory
LMST	local mean solar time
Mars-GRAM	Mars Global Reference Atmosphere Model
MER	Mars Exploration Rovers
MOI	Mars Orbit Insertion
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
POST	Program to Optimize Simulated Trajectories

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